

# Parameter Sensitivity of Soil Moisture Retrievals From Airborne C- and X-Band Radiometer Measurements in SMEX02

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**Abstract**—Among passive microwave frequencies, sensors operating at C- and X-band frequencies have been used with some success to estimate near-surface soil moisture from aircraft and satellite platforms. The objective of this paper is to quantify the sensitivities of soil moisture retrieved via a single-channel single-polarization algorithm to the observed brightness temperature and to retrieval algorithm parameters of surface roughness, vegetation  $B$  parameter, and single-scattering albedo. Examination of the regions within the parameter space that produce accurate soil moisture retrievals reveals that reasonably accurate retrievals can be made over a range of conditions using a fixed set of input parameters. Retrievals with horizontally polarized brightness temperature observations are more consistent than with vertically polarized observations. At horizontal polarization, sensitivity to the input parameters is much greater for wet soils than for dry soils, whereas for vertical polarization the moisture dependence is much weaker. At vertical polarization, sensitivities to variations in all parameters are much lower. To ensure that retrieval accuracy specifications are consistently met, high soil moisture conditions should be used in defining parameter accuracy requirements. Given the spatial and temporal variability of vegetation and soil conditions, it seems unlikely that, for regions with substantial rapidly growing vegetation, the accuracy requirements for model parameters in a single-frequency, single-polarization retrieval algorithm can be met with current satellite products. For such conditions, any soil moisture retrieval algorithm using parameterizations similar to those of this study may require multiple frequencies, polarizations, or look angles to produce stable, reliable soil moisture estimates.

**Index Terms**—Microwave radiometry, parameter space methods, sensitivity, Soil Moisture Experiments in 2002 (SMEX02), soil moisture, vegetation.

## I. INTRODUCTION

THE potential for accurate estimation of soil moisture in the upper few centimeters has been demonstrated in many previous studies using microwave radiometers at various frequencies. L-band ( $\sim 1.4$  GHz) is generally considered the optimal frequency for soil moisture retrieval [1], but sensors operating at higher frequencies, such as S-band ( $\sim 2.6$  GHz), C-band ( $\sim 7$  GHz), and X-band ( $\sim 10$  GHz) have also been used with varying degrees of success [2]–[4]. As frequency increases, so

do the complications due to surface roughness, vegetation scattering and attenuation, and atmospheric attenuation. Furthermore, the soil depth emitting the energy detected by the radiometer is proportional to wavelength. At L-band this emitting depth is on the order of 5 cm, but it decreases to about 1 cm for the higher C- and X-band frequencies [5].

Engineering challenges have hindered development of a space-based L-band sensor, although two are planned to be launched by 2010—Soil Moisture and Salinity Mission (SMOS) [6] and Hydrosphere State Mission (HYDROS) [7]. Sensors at higher frequencies [Scanning Multichannel Microwave Radiometer (SMMR) and Special Sensor Microwave/Imager (SSM/I)] have been operational since the late 1970s. The Advanced Microwave Scanning Radiometer for the Earth Observing System (AMSR-E) consisting of C- and X-band radiometers was launched on the National Aeronautics and Space Administration (NASA) Aqua platform in 2002 [8].

There is much remaining uncertainty about the accuracy, limitations imposed by vegetation mass, and sensitivity of estimated soil moisture to the parameters used in the retrieval algorithms. Parameters are used in the algorithms to describe the soil surface roughness as well as the vegetation properties, both of which are highly variable in space and time. There has been very little research performed to determine the parameter estimation accuracies required to meet soil moisture retrieval accuracy specifications. In an earlier paper [9], we analyzed model parameter sensitivity using aircraft L-band data and found while using horizontally polarized brightness temperatures that certain parameter vectors could produce accurate soil moisture retrievals on all days analyzed. However, very high parameter sensitivity for wet conditions caused the retrievals to be unstable. At vertical polarization, parameter sensitivities were found to be much lower.

The objective of the current paper is to extend the earlier analysis to C- and X-bands by carefully examining and quantifying the sensitivities of soil moisture retrieved via a single-channel, single-polarization algorithm to the model parameters describing the land surface. Although the algorithms ultimately utilized for space-based soil moisture retrievals are likely to use observations at multiple frequencies or polarizations, a thorough examination of the parameter sensitivities for the single-channel, single-polarization model is needed in order to predict retrieval performance and limitations of the more complex models. We performed the analysis for the four frequency-polarization combinations separately to better understand the sensitivity issues of each. We believe that, even if single-frequency, single-polarization schemes may not be ideal, a study such as

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this one provides insight into the strengths and weaknesses of each frequency and polarization. Use of a dual-frequency or dual-polarization algorithm may improve model sensitivity, but the deficiencies are still there and need to be understood.

## II. MEASUREMENTS

### A. SMEX02 Experiment

Soil Moisture Experiments in 2002 (SMEX02) was conducted in central Iowa from June 24–July 12, 2002 to validate AMSR-E remote sensing observations [10]. This agricultural region was selected in part due to its simple landscape, consisting primarily of corn and soybeans in large homogeneous fields, facilitating validation of remote sensing observations and algorithms. Individual fields in SMEX02 were quite uniform in vegetation cover, but there was a very large contrast in vegetation conditions between the two crops. In addition, there was a substantial increase in vegetation density and coverage during the 19-day experiment. Ground sampling teams collected data on a nearly daily basis at field, watershed and regional scales for validation efforts (see below). Aircraft-borne microwave radiometers and radars at L- and S-bands [11] and C-band [Polarimetric Scanning Radiometer (PSR)] [4] were also utilized to estimate surface soil moisture; these sensors were employed to provide data for validation as well as algorithm development and improvement. In this study, we utilize *in situ* data collected within the small-scale intensive Walnut Creek (WC) Watershed domain of about  $10 \times 20$  km.

### B. Soil Moisture and Vegetation Conditions

Gravimetric soil moisture (GSM) content was measured on 11 mornings during SMEX02, usually between 8:30 and 11:30 LDT, at 31 observation sites within the WC watershed. At each site, four GSM measurements were made for the 0–1 and 0–6 cm layers. Volumetric soil moisture (VSM) content was computed from the mean GSM for each layer using soil bulk density estimated at each site, which ranged from  $1.15$ – $1.25 \text{ kg} \cdot \text{m}^{-3}$ . Daily VSM for the 0–1-cm soil layer, averaged for all sites, is shown in Fig. 1. This soil layer approximates the emitting depths for C- and X-band frequencies and will be used here for comparisons with retrieved soil moisture. During the first half of the experiment, soils in the watershed were very dry. On June 25 (day 176) through July 1 (day 182), near-surface VSM, averaged over all observation sites, decreased slowly from  $0.09 \text{ m}^3 \cdot \text{m}^{-3}$  to  $0.06 \text{ m}^3 \cdot \text{m}^{-3}$ . Measurements were not made during July 2–4 (days 183–185). Light rainfall was distributed sporadically on July 4–5 (days 185–186), increasing mean VSM to about  $0.18 \text{ m}^3 \cdot \text{m}^{-3}$ . On July 6 (day 187), more significant rainfall occurred over the watershed and the mean VSM increased to approximately  $0.27 \text{ m}^3 \cdot \text{m}^{-3}$  on July 7 (day 188). Even heavier rainfall on July 10 (day 191) increased VSM to more than  $0.35 \text{ m}^3 \cdot \text{m}^{-3}$ . The uncertainty in estimating the watershed mean VSM is also indicated in Fig. 1 in the form of  $\pm 2$  standard errors for each daily mean. During the early dry period, the daily standard errors were approximately  $0.005 \text{ m}^3 \cdot \text{m}^{-3}$ , but increased to approximately  $0.015 \text{ m}^3 \cdot \text{m}^{-3}$  with the scattered rains on days 185–186. With the more widespread and heavy rainfall

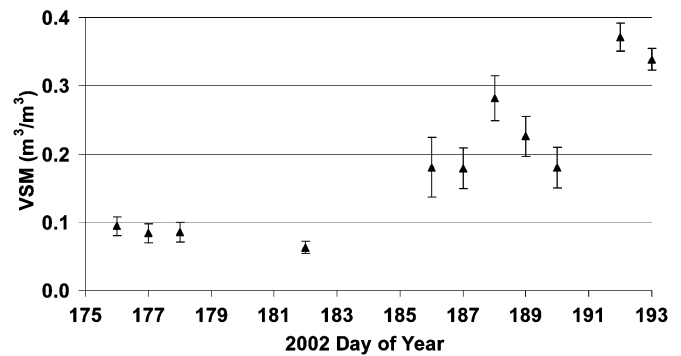


Fig. 1. Time series of 0–1-cm volumetric soil moisture, averaged over the 31 field sites. Vertical bars around the means represent  $\pm 2$  standard errors for the daily mean.

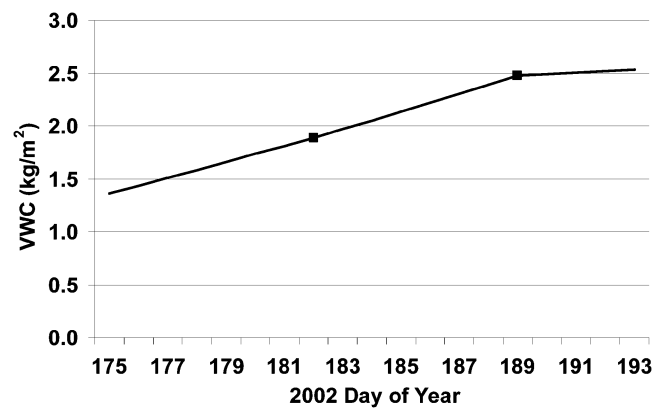


Fig. 2. Time series of vegetation water content means averaged over the study area, derived from remotely sensed NDWI. Squares indicate two of the four days on which NDWI measurements were derived from Landsat observations (observations on days 174 and 197 lie outside the  $x$  axis range).

on days 187 and 191, variability decreased to approximately  $0.010 \text{ m}^3 \cdot \text{m}^{-3}$ .

Vegetation properties including vegetation water content (VWC), plant height and fractional vegetation cover were estimated from Landsat Enhanced Thematic Mapper (ETM) normalized difference water index (NDWI) on June 2 (day 153), June 23 (174), July 1 (182), July 8 (189), July 16 (197), and July 17 (198) [12]–[14]. Estimation of the vegetation properties was accomplished via regression equations for the dominant corn and soybean fields based on Landsat ETM NDWI and *in situ* vegetation observations at the 31 field sites. The root mean square error of the remotely sensed VWC estimates with respect to the corn and soybean field site observations was determined to be approximately  $0.7 \text{ kg} \cdot \text{m}^{-2}$  [13]. We applied the regression equations to each corn and soybean field in the watershed using Landsat ETM NDWI values. A segmentation-based landcover classification we performed using Landsat ETM data [15] indicated that corn and soybeans together composed 79% of the watershed. The other landcover classes that covered substantial area within the watershed were woodland (5.7%), riparian shrub/woodland (5.5%), bare (5.2%), hay (2.7%), and alfalfa (1.9%).

Because we were interested in watershed-scale soil moisture retrieval, we estimated VWC for the other landcover classes within the watershed. To do this, we estimated values for these landcover classes as follows: woodland ( $4.0 \text{ kg} \cdot \text{m}^{-2}$ ), riparian

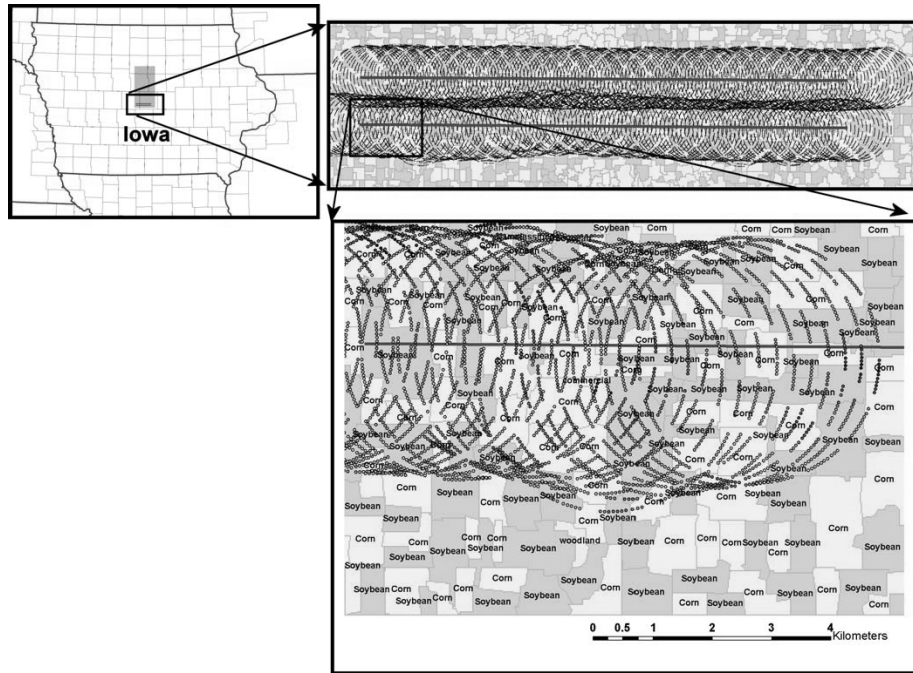


Fig. 3. (Upper left) SMEX02 regional domain (gray box) and area covered by PSR flights on June 25, 2002. (Upper right) Flight lines and ground locations of PSR observations for indicated area, overlaid onto the land cover segments. (Lower right) Close-up of PSR observations, overlaid onto the land cover segments, for a portion of one flight line.

shrub/woodland ( $2.0 \text{ kg} \cdot \text{m}^{-2}$ ), bare ( $0.0 \text{ kg} \cdot \text{m}^{-2}$ ), hay (set to the daily mean soybean value), and alfalfa (set to the daily mean soybean value). We then determined the daily watershed mean VWC from the landcover classification and the estimated or assigned segment (a classified individual field or object with uniform spectral characteristics) VWC values. Linear interpolation was used between the observations to create continuous time series; results are shown in Fig. 2. Over the study period, mean VWC increased from about  $1.4$  to  $2.5 \text{ kg} \cdot \text{m}^{-2}$ . The change in the rate of increase after day 189 is likely an artifact of the interpolation. In terms of variability of VWC within a particular crop type, we found that VWC standard deviations for corn and soybean fields increased with the mean values. The standard deviations ranged from about  $0.44$ – $0.54 \text{ kg} \cdot \text{m}^{-2}$  for corn and from about  $0.10$ – $0.11 \text{ kg} \cdot \text{m}^{-2}$  for soybeans.

Surface roughness was measured at several locations at each SMEX02 field location using the “grid scanning” and “slope scanning” methods [16]. The two methods gave very similar results, with measured roughness values ranging from  $0.5$ – $1.5 \text{ cm}$  with a mean of about  $0.9 \text{ cm}$ .

### C. PSR

The PSR is an airborne conically scanning microwave radiometer with dual polarizations (horizontal and vertical) developed by the National Oceanic and Atmospheric Administration, Environmental Technology Laboratory (NOAA ETL). PSR has C-band (four channels between  $5.82$ – $7.5 \text{ GHz}$ ) and X-band ( $10.7 \text{ GHz}$ ) radiometers, with half-power beam widths of  $10^\circ$  and  $7^\circ$ , respectively. The C and X bands on PSR have similar specifications as the low-frequency channels on AMSR-E. PSR was deployed with a  $55^\circ$  incidence angle onboard NASA’s P-3B aircraft in Iowa during SMEX02. High- and low-altitude flight lines were flown in the regional

and Walnut Creek Watershed areas, respectively. The lower east–west flight lines (Fig. 3) flown over the watershed at a nominal altitude of  $1500 \text{ m}$  were used in this analysis. PSR was flown on 10 days over the watershed area during SMEX02 (June 25, 27, 29 and July 1, 4, 8, 9, 10, 11, and 12). On three of these days ground sampling was not performed, therefore, we have performed analysis for only seven of these days. Flights occurred between  $12:00$ – $14:00 \text{ LDT}$  to coincide with AMSR-E overpasses. Absolute accuracy for the all the PSR observations was better than  $1 \text{ K}$  [17].

### III. MODEL DESCRIPTION

The inverse retrieval algorithm used in this study, a single-channel, single polarization “ $\tau - \omega$  model,” is summarized in [1] and described more completely in [18]. The algorithm employs the surface roughness correction of [19], the vegetation correction of [20] and the effective temperature parameterization of [21]. The dielectric mixing model of [22] was applied. Because the primary intent of this research is to address sensitivity and accuracy issues for AMSR-E, we performed the analysis using inputs representative of mean conditions over the WC watershed, which is on the order of the size of the  $25\text{-km}$  EASE grid on which the AMSR-E products are being produced.

The soil moisture retrieval algorithm requires the following inputs: Brightness temperature (C-band or X-band, horizontally or vertically polarized), surface temperature, deep soil temperature, VWC, soil surface roughness ( $\sigma$ , in centimeters), vegetation  $B$  parameter ( $\text{m}^2 \cdot \text{kg}^{-1}$ ), and single-scattering albedo ( $\omega$ ). Roughness may also be expressed nondimensionally as

$$h = 4\sigma^2 \left( \frac{2\pi}{\lambda} \right)^2 \quad (1)$$

TABLE I

VALUES OF INPUT VARIABLES USED IN THE SOIL MOISTURE RETRIEVAL ALGORITHM, AS WELL AS MICROWAVE EMISSIVITIES. STANDARD DEVIATIONS ARE SHOWN BELOW THE MEANS.  $T_{BH}$ ,  $T_{BV}$  = MEAN H- AND V-POLARIZATION BRIGHTNESS TEMPERATURES (KELVIN) FOR EACH BAND.  $\epsilon_H$ ,  $\epsilon_V$  = MEAN H- AND V-POLARIZATION EMISSIVITIES FOR EACH BAND.  $T_s$  = SURFACE TEMPERATURE (KELVIN).  $T_d$  = DEEP SOIL TEMPERATURE (KELVIN), AND VWC = VEGETATION WATER CONTENT (KILOGRAMS PER SQUARE METER)

Date	C-Band				X-Band				Soil and Vegetation		
	$T_{BH}$	$\epsilon_H$	$T_{BV}$	$\epsilon_V$	$T_{BH}$	$\epsilon_H$	$T_{BV}$	$\epsilon_V$	$T_s$	$T_d$	VWC
June 25	281.2	0.912	290.1	0.941	282.4	0.916	287.5	0.933	309.1	299.3	1.44
	3.2		2.7		4.0		4.1		5.0	1.4	1.06
June 27	281.2	0.923	289.3	0.950	282.5	0.927	288.4	0.947	305.3	297.6	1.58
	3.1		2.8		4.0		3.9		7.2	1.3	1.13
July 1	283.4	0.929	290.0	0.951	285.7	0.937	291.0	0.954	305.5	299.6	1.88
	3.1		2.5		4.1		4.1		4.1	1.2	1.30
July 8	281.9	0.936	289.0	0.960	285.0	0.946	289.6	0.962	301.5	298.0	2.47
	4.5		3.2		4.2		4.9		3.2	0.9	1.69
July 9	282.1	0.934	287.7	0.953	282.8	0.937	286.7	0.950	302.3	297.9	2.49
	3.5		2.6		3.5		3.1		3.8	1.2	1.69
July 11	267.6	0.912	273.7	0.932	269.7	0.918	272.6	0.928	293.5	295.3	2.52
	4.4		3.0		4.6		3.4		2.8	1.2	1.70
July 12	269.7	0.919	275.8	0.939	271.1	0.923	276.4	0.941	293.6	294.2	2.53
	4.1		2.7		4.1		2.7		2.1	1.8	1.70

where  $\lambda$  = wavelength. The first four inputs vary in time and are typically supplied by remote and *in situ* daily measurements. The last three parameters, while not strictly constant, were assumed to vary on time scales long enough to consider them constant for the 17-day period between the first and last PSR flight days. The vegetation  $B$  parameter and single-scattering albedo are generally treated as functions of landcover type, although the latter may increase as the vegetation becomes more dense [23]. The analysis conducted in this study was in part designed to evaluate whether acceptable soil moisture retrievals can be made using fixed values of these parameters.

Values of the input temperatures, microwave emissivities and VWC used in the retrieval algorithm are shown in Table I. We used the watershed means of the PSR observations on each day for the brightness temperature inputs. Vegetation water content estimates were derived from aircraft-based remotely sensed NDWI as described above. Soil temperature means were calculated each day using the *in situ* observations from the 31 field sites. The surface temperatures are from measurements of the soil surface taken at four points within each field with a hand-held infrared thermometer. The deep soil temperatures are from the mean of the 10-cm soil temperatures measured at 14 points in each field [24].

#### IV. PARAMETER SPACE AND MODEL SENSITIVITY ANALYSIS

##### A. Brightness Temperature Response to Soil Moisture Changes

In order to analyze the sensitivities of retrieved soil moisture to model parameters, it is first necessary to determine that C- and X-band brightness temperatures ( $T_B$ ) are responding to changes in soil moisture in this environment characterized by vegetation water contents which, averaged over the watershed, reached  $2.5 \text{ kg} \cdot \text{m}^{-2}$  by the end of SMEX02. At these VWC levels, transmissivity of the vegetation layer at C and X bands is quite low. For opaque vegetation, soil moisture retrieval would be impossible; we have examined changes in microwave emissivities to determine whether there is a detectable  $T_B$  response

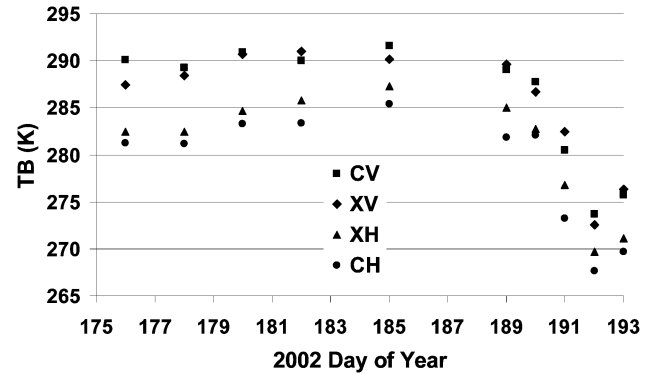


Fig. 4. Watershed mean brightness temperatures for each band from PSR measurements.

TABLE II

RANGES AND INCREMENTS FOR INPUT VALUES OF THE THREE PARAMETERS USED IN THE SENSITIVITY ANALYSIS

Parameter	Minimum	Maximum	Increment
$\sigma$ (cm)	0.00	0.75	0.03
$\omega$	0.00	0.15	0.01
$B$ ( $\text{m}^2 \cdot \text{kg}^{-1}$ )	0.05	0.35	0.02

to soil moisture changes. As shown in Table I and Fig. 4, brightness temperatures at each frequency/polarization combination dropped 15–20 K between July 1 (day 182) and July 11 (day 192) due to rainfall on July 4–10 (days 185–191). However, much of this difference is attributable to decreases in surface temperature. By examining changes in emissivity we can more accurately determine the response to soil moisture. However, increases in VWC also contribute to higher emissivities. A comparison of emissivities for the shorter time interval of July 9–11 reduces the influence of the continuous increases in VWC on emissivity. Table I shows decreases in emissivities of approximately 0.02 from July 9–11 in spite of a slight increase in VWC. Referencing this to a constant effective temperature of 300 K implies an approximate 6 K  $T_B$  response for all frequency/polarization combinations. Mean volumetric soil moisture increased from  $0.18 \text{ m}^3 \cdot \text{m}^{-3}$  to  $0.37 \text{ m}^3 \cdot \text{m}^{-3}$  during this time, indicating a normalized  $T_B$  response of approximately 1 K per  $0.03 \text{ m}^3 \cdot \text{m}^{-3}$ . While this may seem to be a large  $T_B$  response, particularly at X-band, for VWC values exceeding  $2.0 \text{ kg} \cdot \text{m}^{-2}$ , it should be noted that the watershed is composed of roughly equal parts corn and soybeans, which had VWC values on July 9 of approximately 4.0 and  $0.75 \text{ kg} \cdot \text{m}^{-2}$ , respectively [9]. Analysis of “pure postings” (those observations for which at least 95% of the signal arises from a single landcover segment) shows that the normalized  $T_B$  response for soybean areas is two to three times greater than that for corn. Therefore, the overall  $T_B$  response of 1 K per  $0.03 \text{ m}^3 \cdot \text{m}^{-3}$  estimated for the watershed is primarily attributable to the relatively sparsely vegetated soybean fields as well as the other landcover types such as pasture and bare soil which compose almost 20% of the watershed.

##### B. Parameter Space Analysis

In this study, we evaluated the sensitivities of retrieved moisture to the model parameters by performing a suite of retrievals using parameter combinations spanning a three-dimensional parameter space ( $\sigma$ ,  $B$ ,  $\omega$ ). “Sensitivity” refers here to the

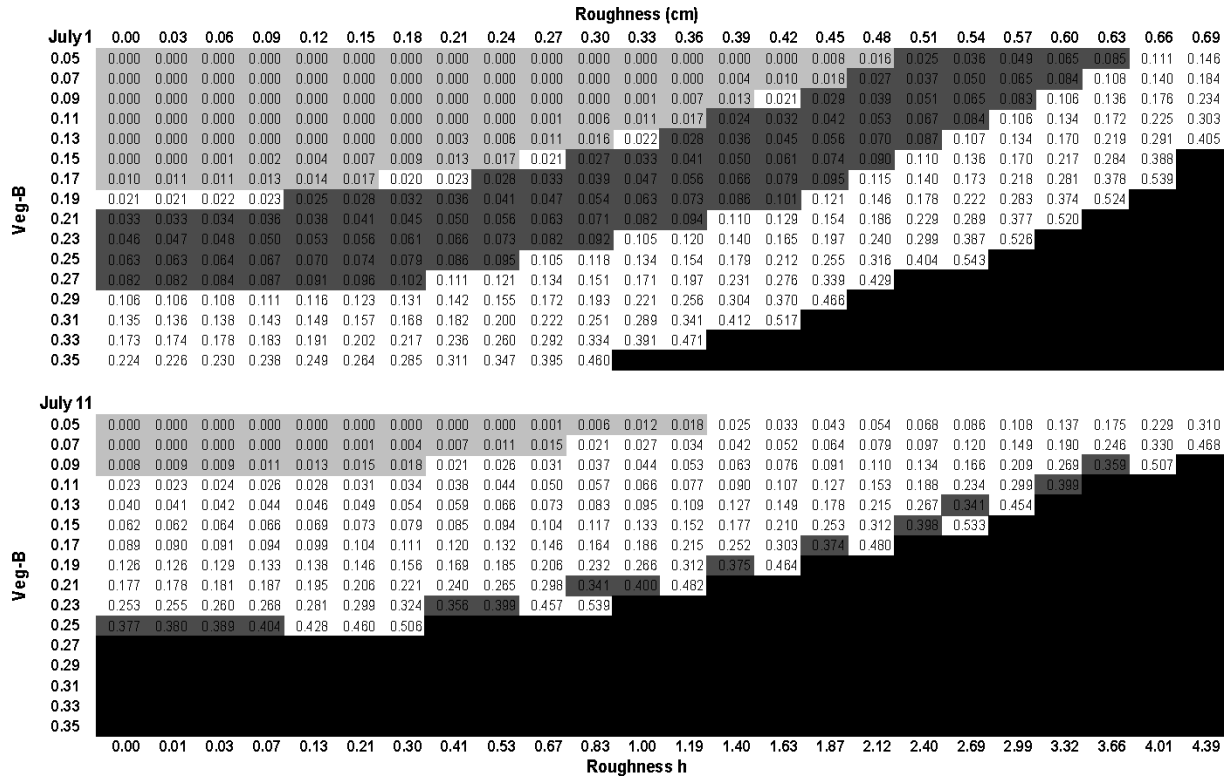


Fig. 5. CH parameter spaces for (top) July 1 and (bottom) July 11 with single-scattering albedo = 0.03. Values shown are the retrieved VSM for each roughness/ $B$ -parameter combination. Values highlighted in dark gray are within  $0.04 \text{ m}^3 \cdot \text{m}^{-3}$  of the mean of the observations. Cells shaded light gray indicate values below  $0.02 \text{ m}^3 \cdot \text{m}^{-3}$  and are considered unrealistically low. Cells with no values represent unrealistically high soil moisture whereby retrieved values are greater than the soil porosity.

change in retrieved soil moisture per change in the parameter. The ranges and increments for each parameter used in these retrievals are shown in Table II. These ranges were guided by previous studies and adjusted in some cases based on preliminary analysis. At C-band, previous investigations have reported values of the  $B$  parameter in the range of  $0.13\text{--}0.19 \text{ m}^2 \cdot \text{kg}^{-1}$  for corn and  $0.24\text{--}0.44 \text{ m}^2 \cdot \text{kg}^{-1}$  for soybeans [20].  $B$  parameter values at X-band are higher, estimated as  $0.34 \text{ m}^2 \cdot \text{kg}^{-1}$  for corn and greater than  $1.0 \text{ m}^2 \cdot \text{kg}^{-1}$  for soybeans, although X-band studies are less numerous [25]. Single-scattering albedo was estimated to be approximately 0.11 for soybeans in [2]. The range of  $0.0\text{--}0.75 \text{ cm}$  utilized for  $\sigma$  does not span the entire observed range of  $0.5\text{--}1.5 \text{ cm}$  and is below the observed mean of  $0.9 \text{ cm}$ , but valid VSM retrievals were not obtained for roughness values greater than  $0.75 \text{ cm}$ .

Most of the results presented here represent a view of the parameter space in one or two dimensions. Our original hypothesis, based in part on the assumption of fixed parameters, was that there would be day-to-day consistency between the regions within the parameter space that produce soil moisture retrievals that agree well with *in situ* observations. This hypothesis has been tested by analyzing the daily parameter spaces for each of the seven days for which PSR data are available. Comparisons of the retrieved and observed soil moisture values across the parameter space help identify the parameter combinations that yield accurate moisture estimates for each day. By fixing two parameters and allowing the third to vary, we evaluate the sensitivity of retrieved VSM to a given parameter. The emphasis is on C-band horizontal polarization, but results for X-band and for vertical polarization are also presented.

Soil moisture values retrieved using C-band, H-pol (CH) brightness temperatures across the full range of surface roughness and vegetation  $B$  parameter values for July 1 (day 182) and July 11 (day 192) are shown in Fig. 5. These two days represent the driest and wettest conditions observed during SMEX02, with mean observed  $0\text{--}1\text{-cm}$  VSM of  $0.063 \text{ m}^3 \cdot \text{m}^{-3}$  and  $0.371 \text{ m}^3 \cdot \text{m}^{-3}$ , respectively. In Fig. 5, retrieved soil moisture within  $0.04 \text{ m}^3 \cdot \text{m}^{-3}$  of the observed  $0\text{--}1\text{-cm}$  mean are highlighted in dark gray, unrealistically low values (less than  $0.02 \text{ m}^3 \cdot \text{m}^{-3}$ ) are shown in light gray, and unrealistically high values (greater than the soil porosity) are shown in black. On July 1 there is a large “valid parameter space” (dark gray), i.e., there are many parameter combinations that yield acceptable soil moisture retrievals. The large valid parameter space illustrates the compensatory nature of the interplay between surface roughness and the  $B$  parameter. As either parameter increases, retrieved soil moisture also increases, so that any increase in one parameter must be offset by a decrease in the other to maintain an accurate moisture retrieval. For wet conditions on July 11, the valid parameter space is much smaller, confined to a narrow band from  $\sigma = 0.0 \text{ cm}$ ,  $B = 0.25 \text{ m}^2 \cdot \text{kg}^{-1}$  to  $\sigma = 0.69 \text{ cm}$ ,  $B = 0.06 \text{ m}^2 \cdot \text{kg}^{-1}$  (by interpolation). All of the July 11 valid parameter region for  $\sigma < 0.45 \text{ cm}$  lies within the region of July 1.

Ideally, the same parameter combinations would be appropriate across a wide range of soil moisture conditions. We have evaluated how well this condition is met by performing parameter space analysis for all seven days of PSR data and counting the number of days that each parameter combination is within  $0.04 \text{ m}^3 \cdot \text{m}^{-3}$  of the *in situ* observation. The results, shown in

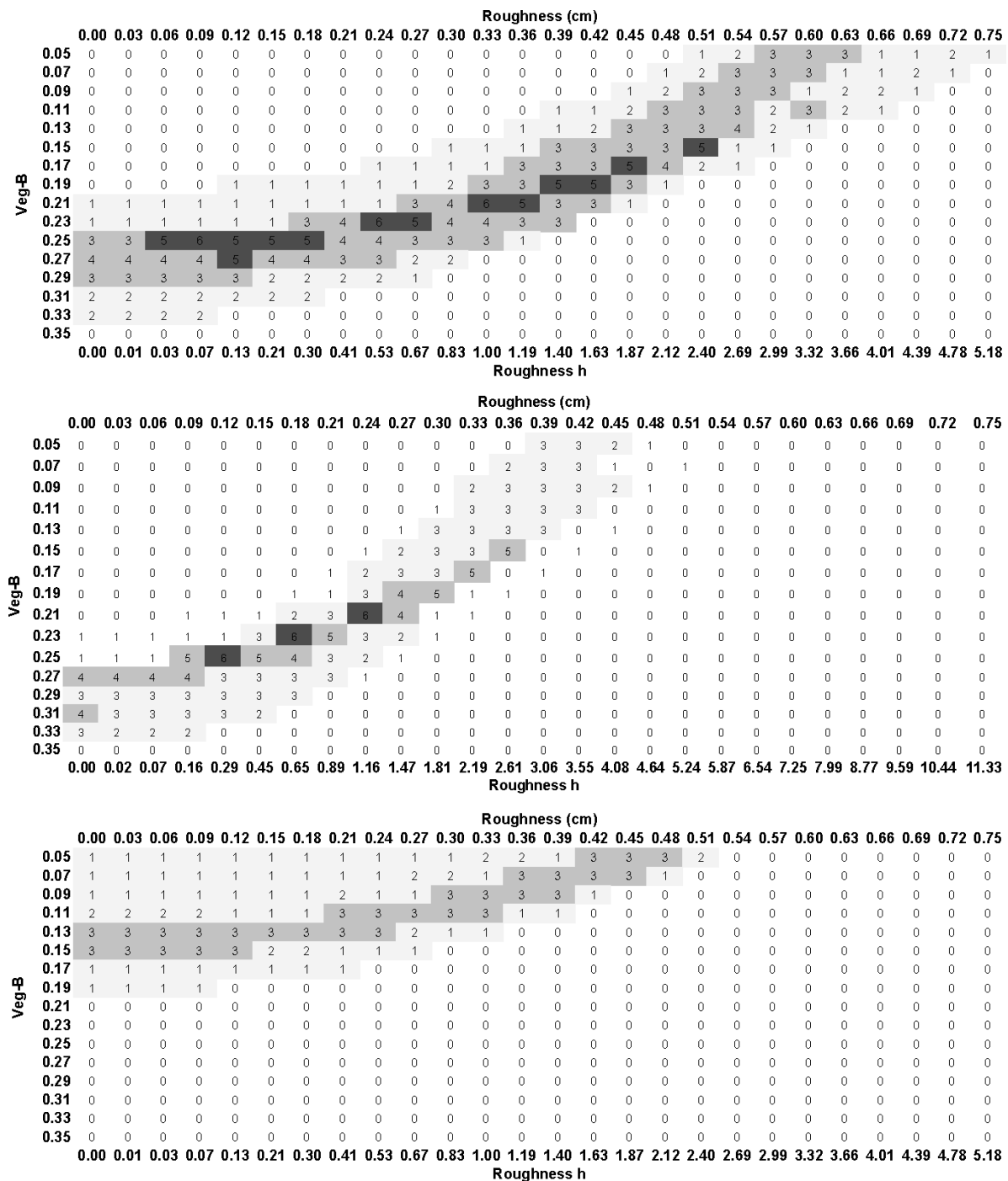


Fig. 6. Number of soil moisture retrievals within  $0.04 \text{ m}^3 \cdot \text{m}^{-3}$  of the daily 0–1-cm observed values, out of seven daily retrievals. Single-scattering albedo =  $0.03$ . Colors from light to dark indicate increasing numbers of days with accurate retrievals. (Top) C band, H-polarization. (Middle) XH. (Bottom) CV.

Fig. 6 for CH, XH, and CV retrievals, show structure similar to that shown for single days in Fig. 5. For CH, the region with accurate retrievals on at least five days extends from  $\sigma = 0.06 \text{ cm}$ ,  $B = 0.25 \text{ m}^2 \cdot \text{kg}^{-1}$  through  $\sigma = 0.51 \text{ cm}$ ,  $B = 0.15 \text{ m}^2 \cdot \text{kg}^{-1}$ . Within this region there are a few parameter combinations for which acceptable retrievals were obtained on six days but none that produced acceptable results on all seven days. In each case where acceptable retrievals were made on six days, the day for which retrievals are not accurate is July 8. The valid regions for the wet days (July 8, 9, 11, and 12) are quite narrow, making exact parameter agreement for all days unlikely.

The middle panel in Fig. 6 shows the number of accurate retrievals across the parameter space for XH. The optimal region is similar to that for CH, except for a slight shift toward lower roughness values for a given  $B$  parameter. As with CH, the maximum number of days for which accurate retrievals were obtained was six. Mapping the parameter space in terms of the roughness  $h$  values (bottom labels), which normalizes for frequency, instead of  $\sigma$ , would render CH and XH results very similar.

The number of accurate soil moisture retrievals using CV brightness temperature inputs is shown in the bottom panel of

TABLE III  
VALUES OF THE PARAMETER REFERENCE POINTS  
USED IN THE SENSITIVITY ANALYSIS

Parameter	CH	CV	XH	XV
$\sigma$ (cm)	.24	.06	.24	.06
$\omega$	.03	.03	.03	.03
$B$ ( $\text{m}^2 \cdot \text{kg}^{-1}$ )	.23	.07	.21	.07

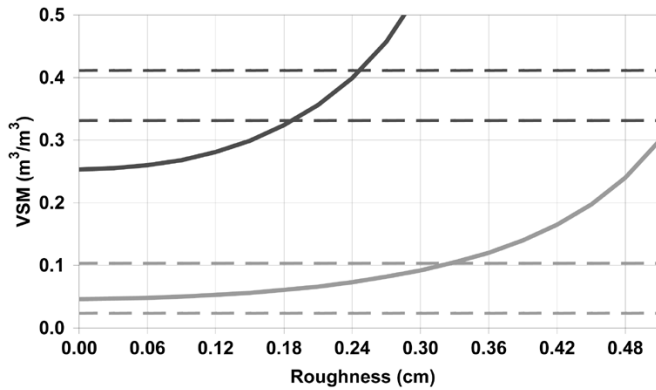


Fig. 7. Sensitivity to surface roughness of VSM retrieved using CH-band  $T_B$  with single-scattering albedo = 0.03 and vegetation  $B = 0.23 \text{ m}^2 \cdot \text{kg}^{-1}$ . The upper and lower curves correspond to July 11 and July 1, respectively. The dashed lines indicate the observed mean  $\pm 0.04 \text{ m}^3 \cdot \text{m}^{-3}$  for each day.

Fig. 6. Soil moisture was overestimated for the three driest days (June 25, June 27, July 1) for all parameter combinations within the selected ranges. For three of the four wetter days (July 8, 11, 12), the valid parameter ranges were very consistent, with accurate soil moisture retrievals being obtained for at least two days within a band extending from  $\sigma = 0.0 \text{ cm}$ ,  $B = 0.13 \text{ m}^2 \cdot \text{kg}^{-1}$  to about  $\sigma = 0.51 \text{ cm}$ ,  $B = 0.05 \text{ m}^2 \cdot \text{kg}^{-1}$ . For July 9, accurate retrievals were obtained only for very low roughness and  $B$  parameter values. Results for XV (not shown) were similar.

### C. Surface Roughness Sensitivity

The sensitivity of the retrieval model to errors in each input parameter has been examined using the suite of soil moisture retrievals performed. For each frequency and polarization, we first determined a “reference point” within the parameter space, which is a given combination of surface roughness, vegetation  $B$  parameter and single-scattering albedo that is as close as possible to a best fit solution for all seven PSR days. We are not proposing this as a unique parameter solution; it is simply one parameter combination for which soil moisture retrievals are reasonably accurate and around which we assess parameter sensitivity. The emphasis here is on the change in retrieved VSM as a function of the change in parameters, not in the retrieved VSM in an absolute sense. The reference points are shown in Table III.

For CH, the model sensitivity to surface roughness is shown in Fig. 7 for July 1 and July 11. In these and similar figures, one parameter (here  $\sigma$ ) is varied while the other two parameters (here  $\omega$  and  $B$ ) are held constant at their reference points. Obviously, a different reference point would yield different results; nonetheless, this figure provides a general representation of model sensitivity. The dashed lines in Fig. 7 show the observed mean VSM  $\pm 0.04 \text{ m}^3 \cdot \text{m}^{-3}$  for each day, i.e., the tolerance intervals for remote sensing as used in the parameter space

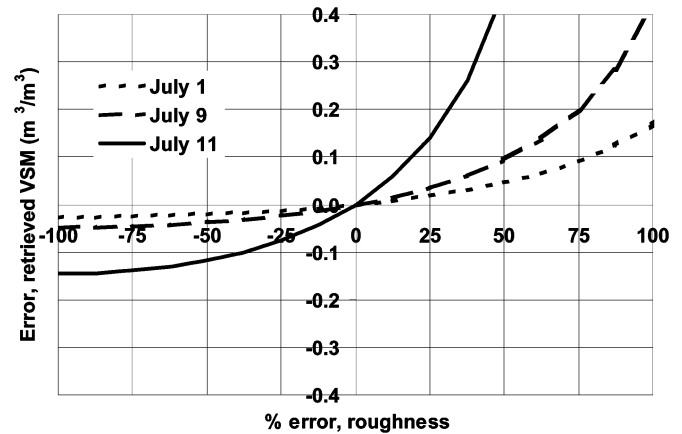


Fig. 8. Errors in VSM retrieved using CH-band  $T_B$  as functions of percent error in roughness for July 1, 9, and 11.

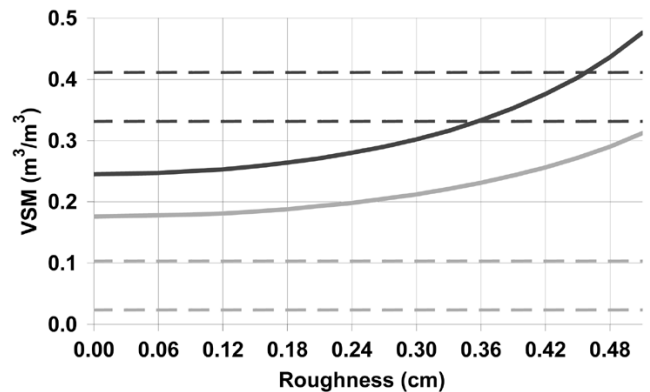


Fig. 9. Sensitivity to surface roughness of VSM retrieved using CV-band  $T_B$  with single-scattering albedo = 0.03 and vegetation  $B = 0.07 \text{ m}^2 \cdot \text{kg}^{-1}$ . The upper and lower curves correspond to July 11 and July 1, respectively. The dashed lines indicate the observed mean  $\pm 0.04 \text{ m}^3 \cdot \text{m}^{-3}$  for each day.

analysis. For July 1, the slope of the curve (i.e., sensitivity) is small within the  $\pm 0.04 \text{ m}^3 \cdot \text{m}^{-3}$  bounds and thus the retrieved VSM lies within the tolerance interval over a wide range of roughness values. For the wet conditions of July 11, sensitivity is greater and the retrieved VSM lies within the tolerance interval over a much smaller range of  $\sigma$ . For XH (not shown), model sensitivities are slightly higher than for CH.

A different characterization of the model sensitivity to surface roughness is shown in Fig. 8 for CH. Here “error” refers to the difference between the VSM for a given retrieval and that retrieved using the reference point, and is plotted as a function of the percent “error” in surface roughness. For the wet conditions of July 11, even a small (+25%) error in surface roughness results in an absolute error in retrieved VSM of greater than  $0.10 \text{ m}^3 \cdot \text{m}^{-3}$ . For the dry case (July 1), the errors resulting from a 25% roughness error are much smaller at around  $0.01\text{--}0.02 \text{ m}^3 \cdot \text{m}^{-3}$ . Errors for the moderately wet conditions on July 9 are between those of the dry and wet days.

Fig. 9, illustrating model sensitivity to surface roughness for CV, indicates two salient characteristics. First, the sensitivity for both dry and wet cases is low. Second, VSM is overestimated, even at zero roughness, for the dry conditions of July 1 (as well as for June 25 and June 27, not shown). In fact, for these days soil moisture is overestimated for CV for all simulated parameter combinations. For July 11 and the other moderately wet to

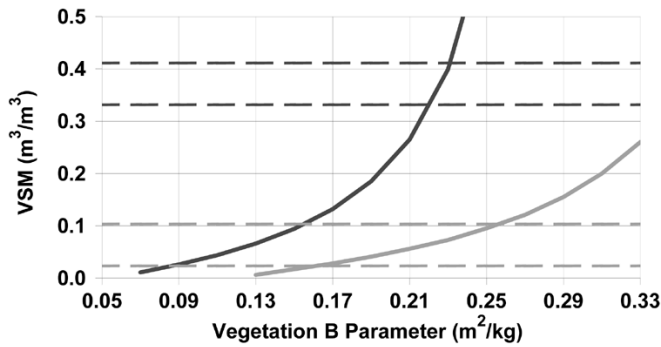


Fig. 10. Sensitivity to vegetation  $B$  parameter of VSM retrieved using CH-band  $T_B$  with single-scattering albedo = 0.03 and surface roughness = 0.24 cm. The upper and lower curves correspond to July 11 and July 1, respectively. The dashed lines indicate the observed mean  $\pm 0.04 \text{ m}^3 \cdot \text{m}^{-3}$  for each day.

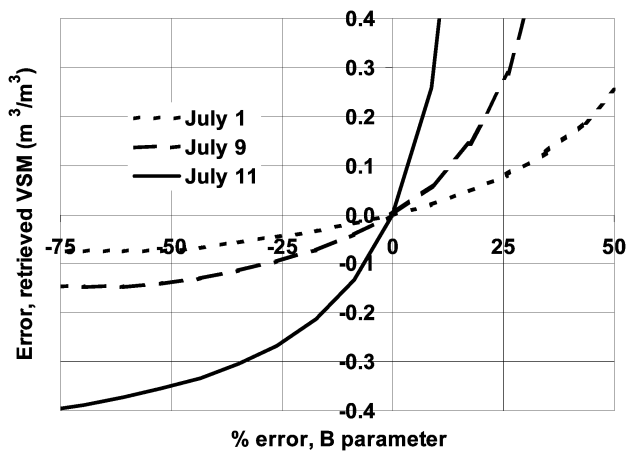


Fig. 11. Errors in VSM retrieved using CH-band  $T_B$  as functions of percent error in vegetation  $B$  parameter for July 1, 9, and 11.

very wet days, accurate soil moisture retrievals are obtained for certain roughness values. Sensitivity for XV (not shown) is intermediate between the CH and CV results. As with the CV case, soil moisture is consistently overestimated using XV brightness temperatures.

#### D. Vegetation Sensitivity

We examined the sensitivity of retrieved soil moisture to vegetation amount by varying the vegetation  $B$  parameter; however, because vegetation optical depth is parameterized as the product of  $B$  and the VWC, an error in estimating  $B$  has the same effect on retrieved soil moisture as a proportional error in estimating VWC. In practice,  $B$  is a fixed parameter for a given landcover class, whereas VWC may have significant temporal and spatial variability, especially in agricultural regions. Thus, the sensitivity and error analysis discussed here is applicable for understanding the effects of uncertainties in estimating VWC. Fig. 10 shows that the sensitivity to the  $B$  parameter for CH is very high under the high soil moisture conditions of July 11. For the wet conditions on this day, the valid range for the  $B$  parameter is very small. For the dry conditions of July 1, sensitivity is lower but still significant.

Sensitivity to vegetation is also shown in Fig. 11 in terms of VSM retrieval error as a function of error in the  $B$  parameter (or VWC). For all days, a 20% input error results in an error in

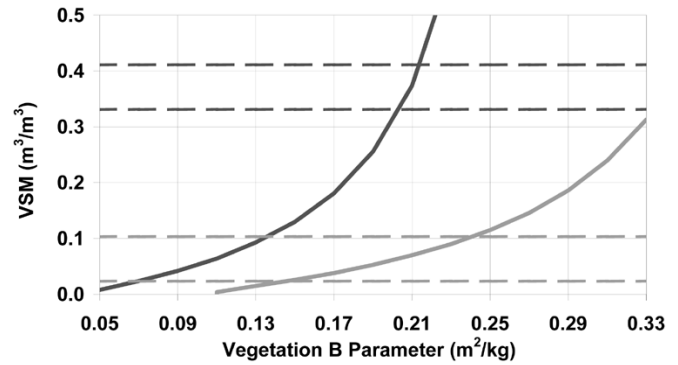


Fig. 12. Sensitivity to vegetation  $B$  parameter of VSM retrieved using XH-band  $T_B$  with single-scattering albedo = 0.03 and surface roughness = 0.24 cm. The upper and lower curves correspond to July 11 and July 1, respectively. The dashed lines indicate the observed mean  $\pm 0.04 \text{ m}^3 \cdot \text{m}^{-3}$  for each day.

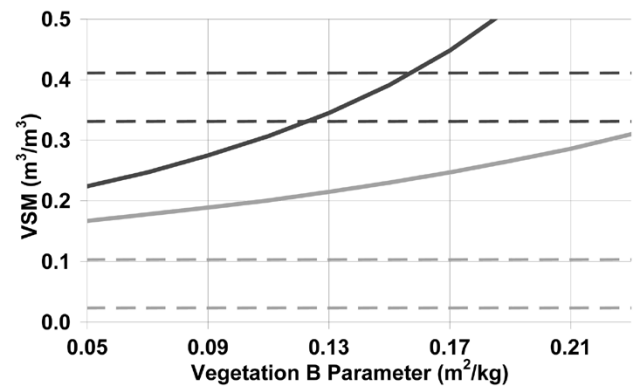


Fig. 13. Sensitivity to vegetation  $B$  parameter of VSM retrieved using CV-band  $T_B$  with single-scattering albedo = 0.03 and surface roughness = 0.06 cm. The upper and lower curves correspond to July 11 and July 1, respectively. The dashed lines indicate the observed mean  $\pm 0.04 \text{ m}^3 \cdot \text{m}^{-3}$  for each day.

retrieved VSM of at least  $0.04 \text{ m}^3 \cdot \text{m}^{-3}$ ; errors are much larger for wetter days. Note that during SMEX02 VWC increased by 20% approximately every four days, implying that if ancillary data are used to specify VWC in an operational retrieval scheme, even if the VWC estimates are error-free, they must be updated on nearly a daily basis in agricultural environments like this in which vegetation conditions are changing rapidly.

Sensitivity to the  $B$  parameter for XH (Fig. 12) is quite high and only slightly less than for CH. By contrast, at CV (Fig. 13) sensitivity is considerably lower than for CH and XH. Soil moisture is again overestimated on July 1. Results for XV (not shown) are similar to those for XH.

#### E. Single-Scattering Albedo Sensitivity

The effect of single-scattering albedo on retrieved VSM for CH is shown in Fig. 14 over a range of  $\omega$  from 0.00–0.06. As with the other parameters, sensitivity is much higher on the wet day, in which case the intersection of the VSM curve and the tolerance interval extends only from about  $\omega = 0.03$  to 0.04. For the dry day, the valid range of  $\omega$  is from approximately 0.015–0.060. For CV, sensitivity to single-scattering albedo, shown in Fig. 15 for three days—July 1 (very dry), July 9 (moderately wet) and July 12 (wet) is much lower than for CH. Because of the slightly different slopes, the July 1 and 9



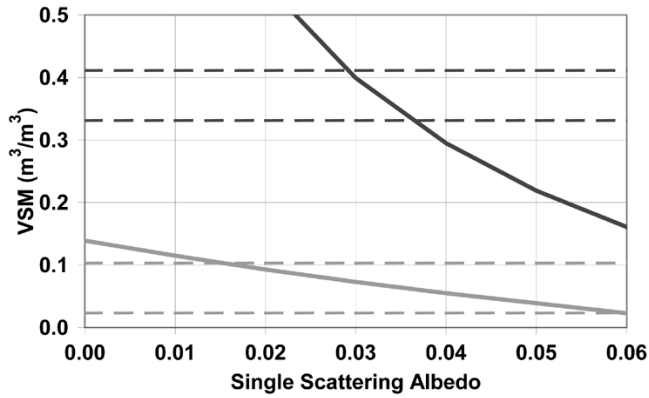


Fig. 14. Sensitivity to single-scattering albedo of VSM retrieved using CH-band  $T_B$  with vegetation  $B$  parameter =  $0.23 \text{ m}^2 \cdot \text{kg}^{-1}$  and surface roughness =  $0.24 \text{ cm}$ . The upper and lower curves correspond to July 11 and July 1, respectively. The dashed lines indicate the observed mean  $\pm 0.04 \text{ m}^3 \cdot \text{m}^{-3}$  for each day.

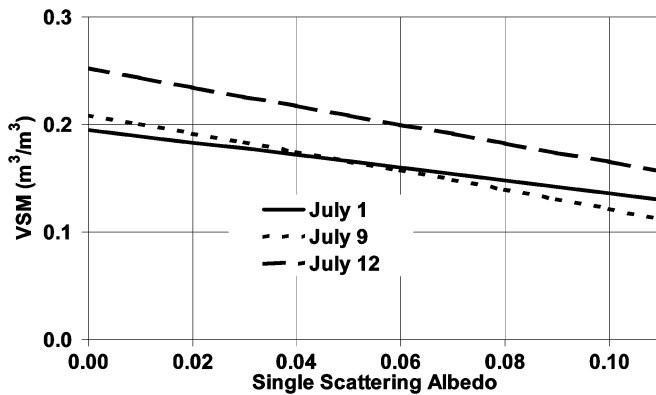


Fig. 15. Sensitivity to single-scattering albedo of VSM retrieved using CV-band  $T_B$  with vegetation  $B$  parameter =  $0.23 \text{ m}^2 \cdot \text{kg}^{-1}$  and surface roughness =  $0.24 \text{ cm}$ .

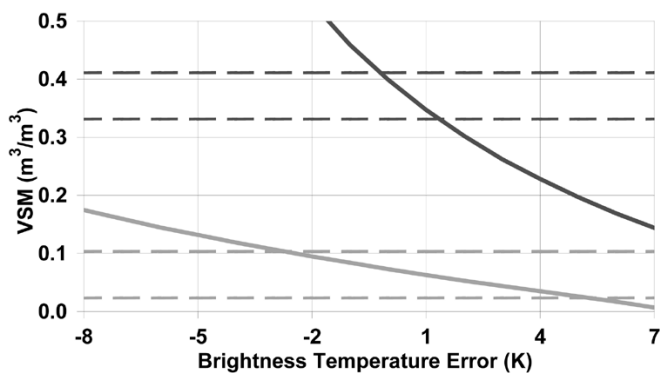


Fig. 16. Sensitivity to CH brightness temperature errors of VSM retrieved using single-scattering albedo =  $0.03$ , surface roughness =  $0.24 \text{ cm}$  and vegetation  $B$  parameter =  $0.23 \text{ m}^2 \cdot \text{kg}^{-1}$ . The upper and lower curves correspond to July 11 and July 1, respectively. The dashed lines indicate the observed mean  $\pm 0.04 \text{ m}^3 \cdot \text{m}^{-3}$  for each day.

curves cross when  $\omega$  exceeds about  $0.05$ . In other words, if  $\omega$  is set too high, the CV retrieval algorithm would not properly differentiate the soil moisture on these two days, which in fact are quite different:  $0.063 \text{ m}^3 \cdot \text{m}^{-3}$  on July 1 and  $0.180 \text{ m}^3 \cdot \text{m}^{-3}$  on July 11.

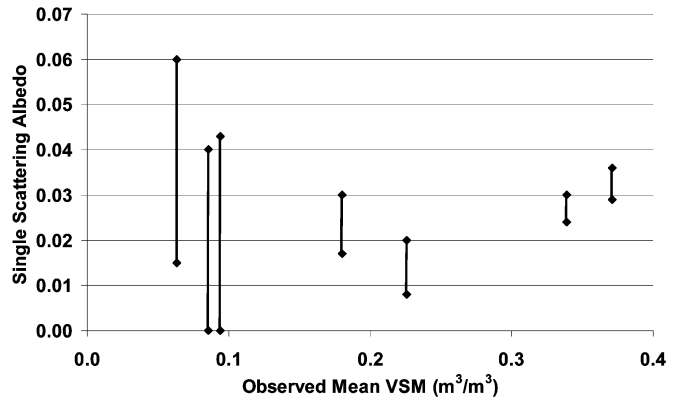
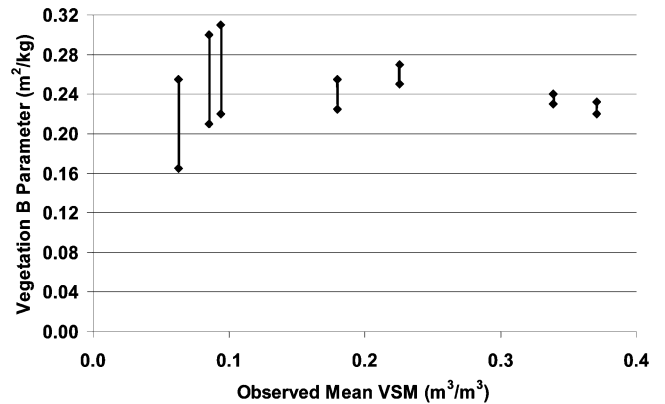
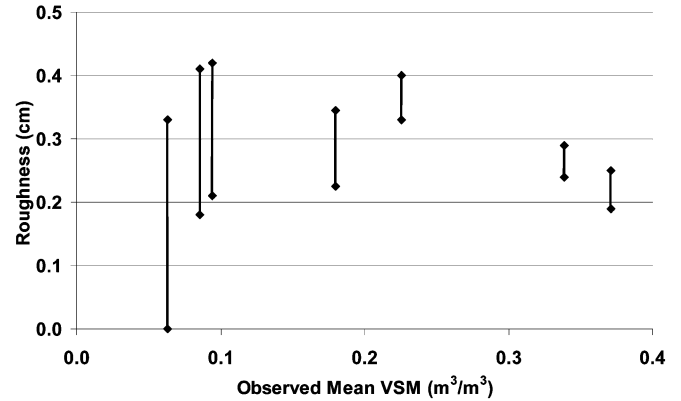


Fig. 17. Valid ranges of (top) roughness, (middle)  $B$  parameter, and (bottom) single-scattering albedo as functions of VSM at C-band, H-polarization.

#### F. Brightness Temperature Sensitivity

Although brightness temperature is not a model parameter, it is important to understand the relative effects of uncertainties in its measurement *vis-à-vis* effects of uncertainties in the three model parameters. Therefore, we performed additional soil moisture retrievals by varying the input microwave  $T_B$  around the observed values; results are shown in Fig. 16 for CH. In these retrievals, the reference points were assumed for the three model parameters. Sensitivity is slightly greater for XH (not shown). For the wet case, sensitivity is quite high at either frequency; a difference of  $1 \text{ K}$  in  $T_B$  can impact retrieved soil moisture by as much as  $\pm 0.04 \text{ m}^3 \cdot \text{m}^{-3}$ . For the dry day, sensitivity is almost an order of magnitude smaller. Sensitivity at V-pol (not shown) is slightly greater than that at H-pol for both frequencies.

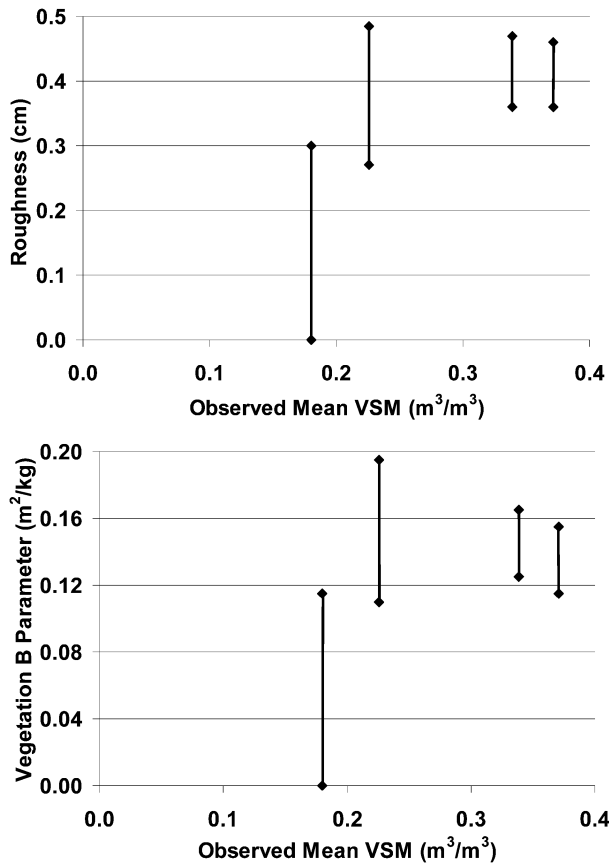


Fig. 18. Valid ranges of (top) roughness and (bottom)  $B$  parameter as functions of VSM at C-band, V-polarization.

### G. Valid Parameter Ranges

To evaluate input parameter error tolerances and how they vary as functions of soil moisture, we determined ranges for each parameter that produce retrieved VSM values within  $\pm 0.04 \text{ m}^3 \cdot \text{m}^{-3}$  of the observations for each day. In determining the valid range for each parameter of the triad, the other two parameters were fixed at their reference points. Fig. 17 shows these valid ranges, plotted against daily observed VSM, for roughness,  $B$  parameter and single-scattering albedo for CH. This is an alternative way to represent the valid parameter regions for all days. The ranges are shown here solely to illustrate the general relationships between soil moisture and the parameter tolerances; because of the interrelated nature of the parameters, the exact ranges of valid parameter values could be quite different for another reference point in the parameter space. For each parameter there is a strong tendency for the range to narrow as soil moisture increases, an obvious consequence of the dependence of model sensitivity on soil moisture. Fig. 18 shows results for CV. Ranges are not shown for the three driest days since there were no parameter combinations that produced accurate VSM retrievals. For the wetter four days, there is again a decrease in the width of the parameter range as VSM increases.

## V. SUMMARY AND CONCLUSION

Using aircraft-based microwave brightness temperature measurements as well as observations of vegetation water content

TABLE IV  
QUALITATIVE SENSITIVITIES OF RETRIEVED SOIL MOISTURE TO EACH MODEL PARAMETER FOR EACH FREQUENCY AND POLARIZATION. VALUES ARE REPRESENTATIVE OF SENSITIVITY FOR HIGH SOIL MOISTURE CONDITIONS

Parameter	CH	CV	XH	XV
$\sigma$	High	Low	High	Moderate
$\omega$	High	Low	High	Moderate
$B$	Very High	Moderate	Very High	High

and soil temperatures for a mixed agricultural region in Iowa, we tested the sensitivity of a standard single-frequency, single-polarization  $\tau - \omega$  soil moisture retrieval algorithm to variations in model parameters. The algorithm was applied independently using C- and X-band brightness temperature observations at both H and V polarizations. Analysis of these results enables us to make inferences about the model's accuracies when applied within the study area. Possible limitations of model application, based on moisture and land cover conditions, are also inferred.

Examination of the three-dimensional parameter space for soil moisture retrievals using either CH or XH brightness temperature observations leads us to conclude that reasonably accurate retrievals can be made using a fixed set of input parameters. For each polarization, there are certain parameter vectors that produce soil moisture retrievals within the specified tolerance of  $0.04 \text{ m}^3 \cdot \text{m}^{-3}$  of the observed values on six of the seven days for which PSR data were available. On the other hand, retrievals were not as consistent at vertical polarization; for the three very dry days studied, the algorithm consistently overestimated soil moisture regardless of the parameter values. At V-pol on the four wetter days, performance was better than for the dry days, with some parameter combinations producing accurate retrievals on three of these days.

A qualitative summary of model sensitivities, assuming wet soil conditions, is given in Table IV. At horizontal polarization, model sensitivity to the three input parameters was found to be much greater when soil moisture is high, whereas for vertical polarization the moisture dependence was much weaker. The moisture dependence stems from the fact that soil surface emissivity is quite high for dry soil and the effects of surface roughness and vegetation on brightness temperature are much smaller than for wet soil. For moderately wet to wet soils, very high sensitivity of retrieved VSM to  $B$  was observed at CH and XH, and there was also high sensitivity to  $\sigma$ . At vertical polarization, sensitivities were much lower to all parameters across the range of VSM.

The sensitivity analysis reveals a paradox. If the sensitivity of the retrieval algorithm is very high, as for the vegetation  $B$  parameter at horizontal polarization, the retrievals are unstable because the accuracy requirements for that parameter are impossible to meet from any data source. On the other hand, when the algorithm is very insensitive, such as for CV to surface roughness and single-scattering albedo, it becomes difficult to counter model biases or input errors via model tuning, with the result that the algorithm may consistently over- or underestimate soil moisture under certain conditions. This is observed for dry conditions at vertical polarization.

TABLE V  
APPROXIMATE ERROR TOLERANCES FOR EACH MODEL PARAMETER AT EACH FREQUENCY/POLARIZATION COMBINATION. VALUES ARE FOR HIGH SOIL MOISTURE CONDITIONS. ROUGHNESS TOLERANCES FOR  $\sigma$  AND  $B$  ARE GIVEN AS PERCENTAGES OF THE TRUE VALUE, WHILE TOLERANCES FOR  $\omega$  AND TB ARE ABSOLUTE

Parameter	CH	CV	XH	XV
$\sigma$	10%	50%	10%	25%
$\omega$	.005	.04	.005	.04
$B$	< 5%	30%	< 5%	15%
TB	1 K	1 K	< 1 K	< 1 K

The analysis presented here can be used to approximate the accuracies required in estimating these parameters in order to reliably retrieve soil moisture using similar single-frequency models in similar mixed agricultural areas. The necessary parameter accuracies depend on moisture conditions; for satellite applications such as AMSR-E, wet soils provide the limiting case in terms of meeting specified error tolerances. In order to ensure that retrieval algorithm specifications ( $\pm 0.04 \text{ m}^3 \cdot \text{m}^{-3}$  tolerance) are consistently met, high moisture conditions should be used to define parameter accuracy requirements. Approximations of these requirements for the SMEX02 study area are given in Table V. Given the spatial variability of vegetation and soil conditions and the temporal changes in vegetation density, it seems unlikely that the accuracy requirements for model parameters used herein can be met with any current satellite-based land surface products. Currently available vegetation indexes from MODIS, for example, are available at eight-day intervals. Meeting the accuracy requirement for the vegetation  $B$  parameter (or VWC) seems particularly problematic. This supports the conclusions of [2] that a single channel algorithm failed to provide robust soil moisture estimates for wheat and soybean crops due to sensitivity to model parameters. In that study, better results were obtained with algorithms utilizing multiple frequencies or look angles, in which some of the surface parameters are retrieved simultaneously with soil moisture. Based on our study, we conclude that for regions with substantial, rapidly growing vegetation, any soil moisture retrieval algorithm that is based on the physics and parameterizations used in this study will require some combination of multiple frequencies, polarizations, or look angles to produce stable, reliable soil moisture estimates.

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